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SEM-BASED AUTOMATIC IMAGE ANALYSIS AND ITS USE IN MINERAL BENEFICIATION - A REVIEW

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ABSTRACT

Automatic image analysis based on SEM signal inputs is termed 'SEM-based AIA'. This analytical tool has been used increasingly in the fields of particle analysis, metallurgy, mineral beneficiation, and food science. Recent improvements in SEM-based AIA include full microscope stage control and integration of an array processor in the image analyser. SEM-based AIA in the mineral processing industry utilizes the instrument's ability to discriminate mineral grains with the backscattered electron signal combined with X-ray spectrometer signals. Immediate benefits are realized because many common ore minerals have similar properties in reflected light and cannot effectively be examined with light optical-based image analysers. With multiple, dedicated image memories, any image or resultant image may be used as the 'pseudo-live' image on which stereological measurements may be made. In the future, a fully software-based image analyser, implemented in the SEM's main computer, could allow the system to be used in process control in an automated mineral processing plant.

L'ANALYSE AUTOMATIQUE DES IMAGES PAR MICROSCOPIE ÉLECTRONIQUE A
BALAYAGE ET SON UTILISATION POUR L'ENRICHISSEMENT DU MINÉRAI :
L'ÉTAT DE LA QUESTION

par

P.R. Mainwaring et W. Petruk

RÉSUMÉ

L'analyse automatique des images fondée sur les signaux d'entrée du MEB est appelée en anglais «SEM - based AIA». Cette méthode analytique est de plus en plus utilisée dans les domaines suivants: l'analyse des particules, la métallurgie, l'enrichissement du minerai et les sciences de l'alimentation. Parmi les améliorations récentes apportées à cette technique, mentionnons entre autres le contrôle total de la platine du microscope et l'intégration d'un processeur vectoriel à l'analyseur d'images. Dans l'industrie du traitement du minerai, on tire parti de la capacité de cet instrument de distinguer les grains de minéral en combinant le signal des électrons rétro-diffusés aux signaux du spectromètre X. Les avantages sont immédiats puisque de nombreux minéraux de minerais communs réagissent de façon semblables à la lumière réfléchie et qu'ils ne peuvent ainsi être examinés de façon efficace au moyen d'analyseurs d'image à base optique. Grâce à des mémoires d'images multiples et spécialisées, toute image ou image résultante peut servir d'image «pseudo-interactive» pour faire des mesures en stéréo. L'implantation d'un analyseur d'images complètement informatisé dans l'ordinateur central du MEB pourrait permettre l'utilisation de ce système dans le cadre de la commande automatique des opérations en continu d'une usine de traitement du minerai.

INTRODUCTION

This paper deals with automatic image analysis (AIA) based on a scanning electron microscope and as used in applied mineralogy in mineral processing. AIA has been available for about 10 years and is considered to mean analysis of features or fields under programmed control. The control functions can be simple - such as following an algorithm to determine area of each particle; or complex - such as finding a particle of specified composition in one or more fields and analysing it quantitatively, as well as determining its size and shape. The purpose of this paper is to review recent developments in the field of SEM-based automatic image analysis and to demonstrate its practical application in the field of mineral beneficiation. The image analysis approach to solving problems in mineral beneficiation was first used in image analysers interfaced with optical microscopes (Petruk 1976) and a microprobe equipped with a travelling stage (Jones 1979). The approach has now been extended to image analysers interfaced with SEM's.

The important advantages of a SEM-based image analysis system lie in the ability to supply compositional data on the minerals, increased speed of analysis, reproducibility of results, and complex data manipulation. Jones and Smith (1978) and Lee and Kelly (1980) have discussed, in detail, some recent advances in the field of SEM-based image analysis, such as grey-level digitizing, thresholding of signals, and digital beam control. Newbury (1981) has discussed the relationship of atomic number contrast, beam current, and beam size in locating objects and imaging in the SEM. The strategy suggested by him provides some practical limits to SEM-based AIA. In this paper we briefly review equipment and methodology or approaches available now in automatic image analysis and then explain the importance of automatic image analysis to applied mineralogists.

IMAGE ANALYSIS AND THE SEM

Image analysers and image analysis techniques can be thought of as instruments or techniques that allow stereological measurements to be made in two dimensions with extrapolation to the third dimension. Until recently, image analysers were most commonly used with light optical

input - either from a video camera focused on the material or the same camera focused on a negative of a SEM micrograph, usually a backscattered image. Light optical-based image analysers suffer from the limitation that their detection capability is hampered by the similar properties of many materials in visible light.

SEM-based image analysis had its beginnings in the work of the Penn State University group working in the early 1970's on particulates, developing computer control of the electron beam and digital image processing of secondary electron output. Byers et al. (1971), Troutman et al. (1974), and Lebedzik et al. (1979) outlined the use of this new method of quantitative characterization of particulate material, largely in the field of atmospheric pollution. LeMont Scientific Ltd. carried the integrated efforts of this group forward with the development of minicomputer control of full SEM-based image analysis.

Development of microprocessors and the subsequent decreasing cost of computing memory rapidly made the incorporation of computers in electron microscopes commonplace. Parallel strides in the development of image processing algorithms has allowed either transforms on live images or stored images (Jones and Unitt 1980, Lee and Kelly 1980, Hardy et al. 1982). Storing of images from the SEM requires at least 0.5 MB of memory per image and frequently several images are required. The most economical approach, in terms of storage, probably lies in the technique of storing only the original BSE, SE, or X-ray dot map image. Further images are produced from these originals by the application of transforms or filters and the Boolean operators. The storage of the original image in dedicated RAM memory and subsequent images on Winchester disk media provides for acceptable image processing times. Several manufacturers offer this technique at the present time including Tracor-Northern, EG&G, KEVEX and others. The image transformations offered by these manufacturers are of little use for application in mineral processing because each mineral in the transformed image must be identified. This identification, which forms the basis of real-time logic decisions, must be determined on the live-image or by digital beam control using the transformed image.

Images from the SEM are analysed in live-time using digital beam control and X-ray spectrometers as described by Hoover et al. (1975), Pawley, Statham, and Menzel (1977), and McCarthy, Fritz and Lee (1981). These authors describe various techniques of discriminating particle

chemistry using solid state spectrometers together with the morphological analysis using digital beam control. This 'live-time' particle analysis requires the slowdown of the digital raster by a significant amount. Estimates of collection dwell time per pixel are about 1-2 microseconds, while several seconds are required for accurate particle characterization by collection of X-ray counts. Details of these now more or less standard techniques are the subject of recent papers by Lee and Kelly (1980) and Jones and Smith (1978).

AUTOMATIC IMAGE ANALYSIS AND MINERAL BENEFICATION

A survey of the applications of automatic image analysis shows that the technique has been successfully applied to numerous fields involving determinative mineralogy of air particulates, coals and coal products (Moza et al. 1979), steel metallurgy (Lee et al. 1981), asbestos and fibre occurrences, (Dixon and Taylor 1979, Stott and Chatfield 1979; Stott et al. 1981), concrete and cement studies (Lebiedzki et al. 1981; Douglas and Mainwaring 1984), and mineral beneficiation (Oosthuyzen 1981, Jones and Shaw 1973, Jeulin 1981).

Since this paper is primarily concerned with applications in mineral beneficiation, we will briefly discuss the importance of SEM-based image analysis to this field of study. Firstly, the objective of mineral beneficiation is the profitable extraction of valuable minerals from raw ores. This extraction begins with grinding which, incidentally, is a very energy-intensive process, to liberate the grains of valuable minerals for further treatment to form a concentrate. This concentrate can then be processed to extract the metals of interest. Grinding of the ore produces free grains and composite or middling grains; the valuable minerals are distributed between these as a function of grinding and the 'grindability' of the ore. The distribution of the wanted minerals must be understood if the grinding is to be effective. This is the step in which the image analyser plays a key role. As suggested here, the efficiency of this process is dependent on the degree of liberation of the valuable minerals from each other and from waste rock. Excessive grinding of the raw ore will be costly and may cause loss of valuable minerals, if they are made too fine to be recovered. On the other hand, insufficient grinding results

in poor mineral recovery, but the plant operator often cannot determine the reason. Based on an examination of the raw ore, the process mineralogist must attempt to answer the question: to what particle size must the ore be ground in order to liberate the required amount of valuable minerals? Subsequently, he must examine the ground ore to confirm his prediction, because the grindability of the rock may alter the result. The advent of the image analyser permits an answer to this problem.

During the past 40 years, the mineral processing industry has been attempting to better characterize raw ores in order to increase metal recoveries and to improve the extraction processes through optimization (Petruk 1984a). Traditionally, this has been carried out by the applied mineralogist with the aid of a light microscope equipped with a horizontally-travelling mechanical stage and a point counter. This technique, little changed, is still in wide use today (Beermann and Tilyard 1983) to derive mineralogical information on mill performance. It has been found that the distribution of particle sizes determined from such linear traverses of the raw ore bears little correspondence to the particle size distribution found when the same material is mechanically crushed. The reason for this lies in the inaccuracy of manually measuring grain diameters as well as in the complexity of transforming linear intercept data to volumetric estimates in 3 dimensions. In addition, Petruk (1978) has shown that the grain sizes as measured in polished sections are not true grain sizes because of the random orientation of the plane of observation.

Development of hard-wired image analysers, such as the Quantimet 720 or Omnicon, has allowed accurate two-dimensional measurements of areas of particles in entire fields, as well as accurate measurements of linear intercepts. Input to these image analysers is in the form of a TV video signal derived from either the optical microscopic image of the particles or from a SEM micrograph (Oosthuyzen 1981). The main drawbacks associated with this type of optical image analyser are the inability to discriminate between most silicate minerals and the mounting medium in which they are set. In addition there is considerable difficulty in discriminating valuable minerals of similar reflectivity but vastly different chemical composition. Petruk (1978) has demonstrated that, because of the accurate measurement, the light optical image analyser has the ability to provide a much higher degree of correlation between grain size distribution of wanted

minerals as measured in polished sections and the distribution found by crushing and sizing the raw ore. The implications of this are that it is possible to answer the question posed above - to predict the liberation of certain minerals from their matrix on grinding, and to confirm that the expected liberation has been obtained.

An alternate approach to the light optical image analyser was made to use the X-ray capabilities of the electron microprobe in discriminating the minerals on the basis of their chemistry. The pioneering work of M.P. Jones at Imperial College (Jones and Gavrilovic 1966, 1968; Jones and Shaw 1973; Jones 1982; Jones and Barber 1975) on mineral particle specimens, using a Cambridge Geoscan electron microprobe equipped with an automated X-Y stage, provides the first attempt to deal with the problems faced by the applied mineralogist. Jones realized that an automated system was the only practicable way of carrying out routine analyses for process and plant control. His method is commonly termed a 'line-measuring' system and consists of linear traverses of the specimen in front of the stationary electron beam. When the beam locates a mineral particle, as determined by the wavelength X-ray spectrometer, that satisfies the search criteria, it is subjected to a series of measurements in much the same way that the area-measuring systems work. A distinct advantage of this line-measuring method lies in the ability to dwell as long as necessary on the particle in order to discriminate the composition accurately. Disadvantages of this technique include: the relatively slow nature of the analysis; interference caused by analysis points too close to contacts between minerals of different composition; the relatively coarse line spacing of the scans which will underestimate the area of the finer particle size material; and the only measurement of the particle is a linear scan at 1 mm - 3 mm intervals, instead of an area measurement.

The SEM with digital scan generator is equipped to produce a raster scan consisting of up to about 4096 X 4096 picture points on the specimen image. Using sampling densities of far less than this, it is possible to locate and measure with reasonable accuracy grains of minerals which are in the order of 2 micrometres in diameter. In general, the use of as many signals as possible as input to the image analyser will increase the speed and effectiveness of the mineral characterization step. On the SEM it is possible to make use of BSE, SF and X-ray signals. Grant et al. (1981), working at CSIRO in Melbourne, have developed an image analysis system that

is fully implemented in software. This instrument, dedicated to use in mineral beneficiation studies, consists of a computer-controlled stage and digital beam control (Miller et al. 1982). These researchers have found that the quantities of minerals determined by the SEM image analysis technique, combined with known chemical compositions of the individual minerals, produces an estimate of bulk composition comparable to that given by bulk chemical analysis.

Jeulin (1981) has developed an SEM-based image analysis system at IRSID, in Paris, France. This system employs a JEOL SEM interfaced to a Leitz TAS automatic image analyser and is in regular use as a mineral beneficiation tool.

SEM-BASED AIA AT CANMET: INSTRUMENTATION AND PROCEDURES

A JEOL 733 electron microscope-based image analysis system with energy dispersive spectrometer, 2 wavelength spectrometers, and an interfaced KONTRON image analyser with 16 image memories has been installed recently in the Mineral Sciences Laboratories at CANMET. A functional block diagram of the system is shown in Figure 1. Advantages of an electron-beam instrument interfaced to an image analyser include the capability of storing several images of the specimen, including the BSE, X-ray dot map and secondary electron images. These images are then processed with sophisticated arithmetic image processing routines. These routines include filter functions, edge enhancement (derivatives), perimeter connection, and full grey level processing. Any of the resultant, enhanced images may then be used as the 'pseudo live-time image' for controlling the positioning of the electron beam to identify selected features in the field. Once these features are selected, the KONTRON image analyser can be programmed to display a measuring frame (Figure 2) around that object for derivation of object specific data, such as shape and size of individual grains. The proportion of intergrown minerals of different types, occurring in complex grains, can also be determined. This measurement is shown in Figure 2 where small inclusions of the mineral chalcopyrite are calculated as a fraction of the entire complex grain and the sizes of the individual inclusions are determined. These object specific subscans may be defined either automatically or interactively which greatly speeds analysis of a

particular frame. Modal analysis, which involves the counting of many grains in numerous fields, is performed through the field specific algorithm. It is possible to mix object-specific measurements with field-specific measurements in a particular analysis routine.

A field-specific measurement of an ore is shown in Figure 3. Successive image memories are loaded with the backscattered electron image of the field and X-ray dot maps that might help to identify particular minerals that may not be discriminated by their backscattered electron intensity. Through adjustment of the BSE threshold discriminator and storage of the binary images in memory, it is possible to detect most minerals in the field. This procedure may be augmented by the use of the appropriate X-ray dot maps if some minerals cannot be discriminated using their BSE signal. The composite image shown in Figure 3 consists of a secondary electron image of the field combined with the grey level image of one mineral, galena. All galena in the field is detected and assigned a false colour for display on the RGB display monitor. Results of these field specific measurements are calculated, for example, as volume percentages of each mineral type for the specimen and mean measurements, such as average perimeter or diameter. Control of the specimen stage by the image analyser allows sequential and rapid movement across the entire specimen.

Another major use of the image analyser at CANMET is in the location and subsequent analysis of minerals which occur in very low concentrations in other materials, such as tailings. In these cases there may be only a single grain of a valuable mineral, e.g. native gold, in many thousands of grains of gangue minerals. One approach to this problem is to use the linear traverse technique while monitoring the output of the wavelength spectrometers which are set for specific elements of interest. When the elements sought are detected, then the grain of interest is positioned under the beam by the image analyser, which controls the stage, and the measurement frame is erected on the grain for stereological measurements. Subsequently, the grain may be quantitatively analysed using the two wavelength spectrometers at a later time.

AN APPLICATION OF AUTOMATIC IMAGE ANALYSIS AT CANMET

Detailed applications of image analysis to mineral beneficiation studies have been presented by Petruk and Schnarr (1981), Jeulin (1981), Grant et al. (1981), Miller et al. (1982) and Oosthuyzen (1981). Mineral beneficiation studies involve the determination of at least six important features of uncrushed feed and crushed ore. The initial step is complete mineralogical characterization of the raw ore. This step involves the use of the optical microscope, SEM, electron microprobe and X-ray diffraction. Following this step, the quantities of each mineral must be determined, either by optical examination of polished sections, quantitative X-ray diffraction, or by image analysis. As mentioned previously, optical determination is hampered by grain size of the minerals, poor discrimination, and operator fatigue. X-ray diffraction techniques are limited by grain size of the material and dilution effects. Automatic image analysis is limited only by availability of instrumentation and operator training. Grain sizes of wanted minerals in raw ore can be determined either by linear traverse methods or by automatic image analysis.

Studies on crushed ores or mill products permit determination of mineral liberation by estimation of free and unliberated mineral proportions. Unliberated wanted minerals are further studied to determine their contribution by volume to middling or intergrown particles. These middling particles must be classified since they may be partitioned either into a concentrate, reducing its grade, or into the tailings, reducing the recovery of the process. Estimation of volume percent of a particular inclusion in a host grain is ideally suited to SEM-based image analysis using spectrometers or the BSE signal to discriminate the inclusion of interest.

At CANMET, we have recently studied the occurrence of free and locked apatite, a calcium phosphate mineral, and niobium minerals in a potential ore. The raw ore (Figure 4) occurs as loose and partially cemented iron oxide-rich silt and sand, a product of extreme weathering of a carbonate-bearing rock. Much of the potentially valuable apatite and niobium-bearing minerals occur locked in cemented aggregates and as inclusions in apatite and hematite that may be classified as middling particles. Because the raw ore is characterized by an extremely wide variation in size of grains and

agglomerated masses, it is a complex material on which to carry out quantitative measurements. This variation in grain size prohibits the selection of a unique magnification in any microscope used to study the ore. Consequently, the number of particles per field would vary greatly, as would their resolution for image analysis. For such ores it is necessary to produce a series of screened fractions on which measurements may be carried out.

Apatite constitutes a large proportion of the samples and consists of two types: one rare earth element-bearing and the other, rare earth element-free. The niobium-bearing minerals of interest are pyrochlore, which contains Ce and La, and ferro-columbite, which contains less niobium than associated pyrochlore (Figure 5). A BSE detector in the SEM must be used to discriminate these two niobium-bearing minerals before their relative abundances and sizes can be measured. The grains of interest, and their average atomic number contrast, are sufficiently great that location and imaging are not problematical.

It is required to measure the sizes of the included apatite, pyrochlore and columbite, together with their volume percentage of the middling particles for each screen fraction. The relationship between inclusion size and its volume percentage in the middling particle can then be plotted (Figure 6). Data for successive screened size fractions may then be combined into a composite for the whole ore sample based on the weight fraction of the particular screen fraction. This complete analysis using fully automated image analysis and mineral identification requires about 30 hours for 5 screened fractions. To carry out a similar operation by manual methods is highly operator dependent and would require several weeks.

SUMMARY

SEM-based automatic image analysis is an important tool for the process mineralogist involved in mineral beneficiation studies. This instrument extends the effectiveness of the normal TV-type input image analyser in the field of mineral beneficiation and quantitative mineralogy. This increased capability is due to the addition of energy dispersive and wavelength spectrometers, automatic control of the SEM

sample stage, and the availability of an array processor. The necessary statistical basis for quantitative mineralogy and particle searching routines both rely on the automated stage under control from the image analyser. Digitally-controlled electron beam positioning allows flexible definition of object-specific parameters such as size, chord, and perimeter measurements.

All these features of modern image analysers ideally suit the applied mineralogy application and it has been suggested (Petruk 1984b) that an SEM-based automatic image analyser could function as a monitoring instrument or sensor in a highly-automated mineral processing plant.

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FIGURE CAPTIONS

- FIGURE 1: Block diagram of SEM-KONTRON image analysis system at CANMET.
- FIGURE 2: Object-specific analysis of a complex mineral grain in secondary electron image from image analyser. The measuring frame is automatically erected by the image analyser program.
- FIGURE 3: A resultant image showing the grey levels for the minerals chalcopyrite and galena, superimposed, by the image analyser, on the secondary electron image of the field.
- FIGURE 4: Polished section of a hollow-centred, cemented, agglomerate consisting of the minerals apatite (AP), hematite (HM), pyrochlore (PYL) and columbite (CMB). Backscattered electron image. Raw ore.
- FIGURE 5: Screened fraction of ore shown in Figure 4. Grain mount, polished section. Simple and complex grains of the minerals pyrochlore (PYL) and columbite (CMB) can be seen. Backscattered electron image.
- FIGURE 6: Graph showing final output form of image analyser data. Fraction of complex grain occurring as inclusion plotted against amount of that fraction occurring in the sample.

FIGURE 1











